# THE TITAN SATURN SYSTEM MISSION—A MULTI-PROBE MISSION TO TITAN AND ENCELADUS

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## ABSTRACT

It is becoming clear that any future mission to Titan would require the delivery and support of *in situ* probes to address high priority science questions raised by both the Cassini-Huygens mission and the international science community participating in recent NASA-ESA mission studies. The most recent studies have specifically identified the montgolfière hot air balloon (Titan's rover) and lake lander as providing the highest value science return for future missions to Titan. Furthermore, results from science, technical, and management review of recent studies have focused current technical efforts on key areas for increasing the readiness of these *in situ* probes for launch. The purpose of this paper is to provide a technical overview of the Titan Saturn System Mission (TSSM) architecture and its elements and the progress and plans toward reducing risk and increasing readiness.

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## 1. INTRODUCTION

The fascinating world revealed by the Cassini-Huygens mission has stimulated great interest in the science community in recent years. Several studies over the last decade have looked at Titan as a world tailor-made for application of techniques that would allow enhanced exploration. In 2007, the APL-led Titan Explorer study confirmed that an architecture consisting of an orbiter with lander and balloon *in situ* probes was optimal for a flagship mission to Titan. This study, along with the ESA TandEM study, formed the basis for the 2008 Titan Saturn System Mission (TSSM) study to develop a mission that would expand on Cassini/Huygens' tantalizing discoveries at Titan and Enceladus, covering a wide range of planetary science disciplines—Geology, Geophysics, Atmospheres, Astrobiology, Chemistry, Magnetospheres—in a single NASA/ESA collaboration [1, 2].

The TSSM baseline mission was derived from a careful consideration of alternative architectures as discussed in [1]. The baseline mission would consist primarily of a Titan orbiter spacecraft augmented with a solar electric propulsion (SEP) stage (Fig. 1), capable of meeting all Level 1 science requirements as imposed by study ground rules and the TSSM joint science definition team (JSDT), including Saturn system science as well as targeted science at Enceladus during an extended Saturn tour phase [1]. The baseline mission would also accommodate two ESA-provided *in situ* probes, a long-

lived montgolfière aerial vehicle that would circumnavigate the moon at a nominal altitude of 10 km (Fig. 2) and a battery-powered lander targeted at Titan's northern lakes (Fig. 3). These probes would be delivered to Titan by the orbiter spacecraft and supported during their science mission with two-way data relay through the orbiter telecom assets (Fig. 4).

The TSSM mission architecture represents a robust and scientifically rich implementation that would produce a giant leap in our understanding of Titan and Enceladus.

## 2. BASELINE MISSION DESCRIPTION

The baseline mission concept developed for TSSM would include a flight system comprised of an orbiter and two *in situ* probes. The flight system would travel by means of an inner planet gravity assist trajectory and reach Saturn approximately nine years after launch. Augmentation of $\Delta V$ is provided during roughly the first two-thirds of the trajectory by using an SEP stage, which would be jettisoned approximately five years into the mission (Fig. 5). Following the remainder of the cruise, the orbiter's chemical propulsion subsystem would place the flight system into orbit around Saturn followed by approximately two years of Saturn system science, including a minimum of seven Enceladus flybys, while the flight system would use repeated satellite gravity assists

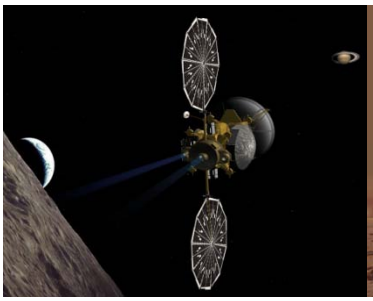

Fig. 1. TSSM flight system concept in SEP cruise configuration.

Fig. 2. TSSM montgolfière concept.

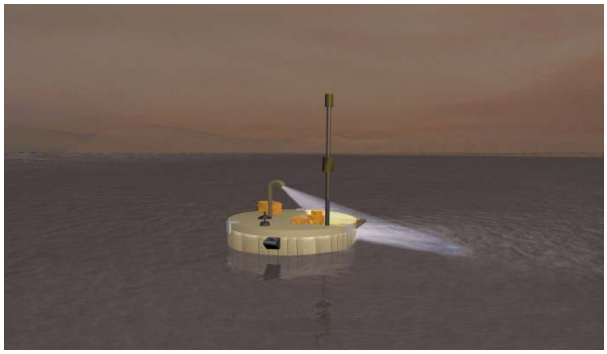

Fig. 3. TSSM lake lander concept.

and maneuvers to reduce the energy needed to insert into orbit around Titan (Fig. 6).

The *in situ* probes delivered by the orbiter would include a montgolfière aerial vehicle and a lake lander. Current planning for the baseline mission is that the montgolfière probe would be released at the first Titan flyby after Saturn orbit insertion (SOI) for ballistic entry into Titan. The lander probe would be targeted and released at the second Titan flyby to ensure robust communications links during its primary mission. Titan orbit insertion would be accomplished at the end of the Saturn tour phase using the main engine. Capture into an elliptical Titan orbit would be followed by a two-month aerobraking and aerosampling phase, leading to a circular 1500 km orbit for the final 20-month orbital science phase (Fig. 7).

At an orbital altitude of approximately 1500 km, the flight system would orbit Titan approximately five times in an Earth day. A science planning payload was developed, consisting of six instruments (Table 1) in addition to radio science, and was estimated at 165 kg (including contingency) with an orbital average power of <90 W (current best estimate [CBE]). The telecom subsystem design was sized to provide a minimum science data downlink from Titan orbit of approximately 5.4 Gb per Earth day, assuming two 8-hour DSN passes per day at maximum range (~10.1 AU). This capability would increase as the Earth-Saturn range decreases over the course of the mission. Science operations for TSSM were structured to address the science objectives, with three observational campaigns optimized for available power and downlink. Key characteristics of the baseline mission concept are listed in Table 2.

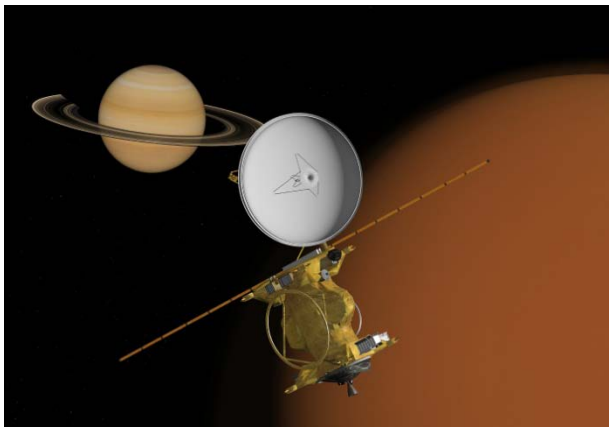

Fig. 4. TSSM orbiter concept.

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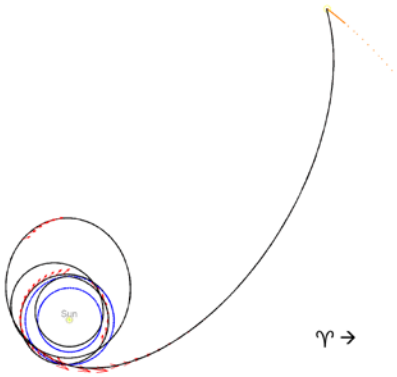

Fig. 5. 2020 EVEE SEP baseline trajectory with arrows showing thrust periods and

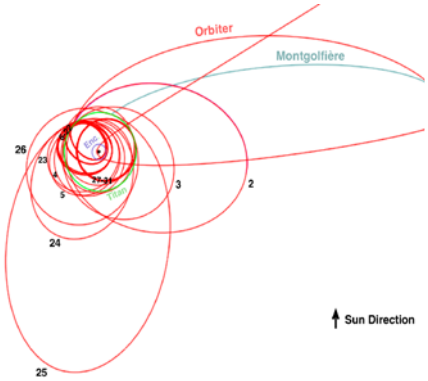


Fig. 6. Planned Saturn tour phase showi orbits numbered from SOI to TOI.

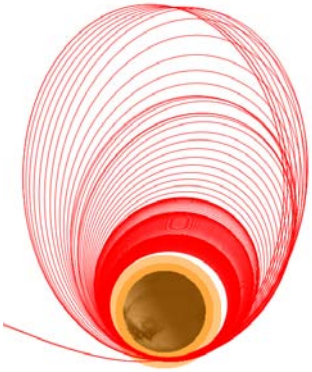

Fig. 7. Aerobraking phase orbits.

Table 1. Orbiter model science instruments and science contributions.

| Inst. | Description | Science Contributions |
|---|---|---|
| HiRIS | High-Resolution Imager [in three colors (~2.0, 2.7, and 5–6 µm)] and Spectrometer (near IR). Two spectral mapping bands 0.85 to 2.4 µm (5 nm spectral resolution) and 4.8 to 5.8 µm (10 nm spectral resolution) | Global surface mapping at 50 m/pixel in three colors. Spectral mapping at 250 m/pixel. Surface composition and atmospheric studies. |
| TiPRA | >20 MHz Titan Penetrating Radar and Altimeter. Two dipole antennas (1st one used for Enceladus and then ejected; 2nd for Titan orbit phase) | Global mapping of subsurface reflectors with 10 m height resolution in altimetry mode and better than 10 m in depth resolution. Lower data rate depth sounding mode with ~100 m depth resolution. Approximately 1 km × 10 km spatial resolution. |
| PMS | Polymer Mass Spectrometer with M/ΔM ~10,000 for masses up to 10,000 Da | Upper atmospheric *in situ* analysis of gases and aerosol precursor aerosampling down to 600 km. Detection limit is better than $10^4$ particles/$cm^3$. |
| SMS | Sub-Millimeter Heterodyne spectrometer with scanning mirror. 300 kHz spectral resolution, 12 km spatial resolution. | Measure winds directly from Doppler. Temperature mapping from ~200–1000 km altitude; Obtain CO, $H_2O$, nitrile and hydrocarbon profiles. |
| TIRS | Thermal Infrared Spectrometer Passively cooled Fourier Spectrometer 7–333 microns. Spectral resolution 0.125–15 $cm^{-1}$. | Organic gas abundance, aerosol opacity and temperature mapping 30–500 km. |
| MAPP | Magnetometer. Tri-axial fluxgate sensors 0–64 Hz. Noise levels of the order 11 pTrms | Measure interaction of field with ionosphere: internal and induced field. |
| | Energetic Particle Spectrometer. TOF analyzer with solid state detectors | Measures ions in the energy range of 2 keV/nucleon to 5 MeV/nucleon and electrons in the range from 20 to 1000 keV with 150° × 15° FOV. |
| | Langmuir Probe—Swept voltage/current probe. | Measure thermal plasmas in Titan's ionosphere over a range of densities from 10 to $10^6$ $cm^{-3}$ and temperatures from 0.01 to 10 eV. |
| | Plasma Spectrometer—Electrostatic analyzer system, with a linear electric field time-of-flight mass spectrometer. | Measures ion and electron fluxes at ~5 eV to a ~5 keV. M/ΔM~10. |
| RSA | Radio Science and Accelerometer. Components are part of the spacecraft bus: USO, transponder, and accelerometers. | Lower stratosphere and troposphere temperature profile. Gravity field. |

Table 2. Key mission characteristics of the TSSM baseline mission concept.

| | |
|---|---|
| **Architecture** | Orbiter with *in situ* probes |
| **Launch vehicle** | Atlas V 551 |
| **Launch date** | 9/2020 |
| **Trajectory** | Earth-Venus-Earth-Earth gravity assist |
| **Flight time to Saturn** | 9 years |

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| | |
|---|---|
| **Saturn system tour phase** | 24 months |
| **Number of close Enceladus encounters during the Saturn tour** | 7 |
| **Number of Titan encounters during the Saturn tour** | 16 |
| **Titan aerosampling phase** | 2 months |
| **Titan orbital phase** | 20 months |
| **Radiation design point*** | <15 krads |
| **Science instruments, mass allocation** | |
| **Orbiter** | 6 plus radio science; 165 kg |
| **Montgolfiére** | 7 plus radio science; ~25 kg |
| **Lake lander** | 5 plus radio science; ~32 kg |
| **Average data volume return from Titan orbit** | 5.4 Gb/Earth day (compressed) |
| **Cumulative data volume** | |
| **Orbiter** | >4.9 Tb |
| **Montgolfiére** | >300 Gb – 1.3 Tb |
| **Lake lander** | >500 Mb – 3.4 Gb |

*Behind 100 mils of Al, RDF of 1

## 3. TSSM FLIGHT SYSTEM OVERVIEW

The TSSM baseline flight system would be composed of three elements—the orbiter, augmented by an SEP stage; a multi-mission radioisotope thermoelectric generator (MMRTG)-powered montgolfière; and a battery-powered lake lander.

### 3.1 Titan Orbiter

The TSSM orbiter (Fig. 8) concept is a three-axis stabilized spacecraft powered by radioisotope power systems (RPSs) that has strong similarity to the Cassini orbiter. The TSSM orbiter would include an articulated 4 m high gain antenna (HGA) using Ka-band for high-rate science data downlink. A planning payload of six instruments plus radio science is accommodated with the model instruments located on a payload deck, as well as other locations on the spacecraft dictated by their observational requirements. Accommodation for the two *in situ* probes would be provided at attachment points along the body of the orbiter. Five advanced stirling radioisotope generators (ASRGs) would power the spacecraft, with four providing a total of 540 W of electrical power at end of mission (approximately 13 years after launch) and the fifth unit carried as a spare. The TSSM architecture would also be compatible with use of MMRTGs if directed by NASA. Redundant 25 A-hr Lithium-ion (Li-ion) batteries would provide for power demands that exceed the RPS capability during the science mapping orbit and at other times during the mission. The launch mass of the flight system is estimated at 6203 kg. This is within current Atlas V 551 capability of 6265 kg to the required launch energy. The flight system design includes ample mass and power margins in excess of what is typically required at this stage of maturity. Use of SEP would allow for significant mass growth of up to 300 kg beyond the current margins with a minimal impact of up to 1.5 years longer flight time.

The TSSM flight system would incorporate an SEP stage for efficient ΔV augmentation during the first half of the cruise trajectory, which is jettisoned after approximately five years. The SEP stage for TSSM was developed as a simple, bolt-on augmentation built around and incorporating the function of a launch vehicle adapter (LVA). The basic LVA structure would be used to support two Orion-derived 7.5 kW Ultraflex solar array wings, as well as three NEXT ion thrusters, power processing units (PPUs), xenon tanks, and electronics necessary for the control and operation of this self-contained stage. Interfaces with the launch vehicle and orbiter were kept simple to allow the flexibility to operate with or without the SEP stage without significant changes to orbiter configuration.

### 3.2 Montgolfière

The montgolfière *in situ* probe concept designed for TSSM is a hot air balloon. An MMRTG would provide both electrical power (~100 W) to the gondola and heat (~1.7 kW) for buoyancy. The balloon envelope concept, nearly 11 m in diameter, uses double-wall construction for improved thermal insulation. An aeroshell with a heat shield, and a back shell, protect the montgolfière from the thermal load of entry (Fig. 9).
The orbiter would carry the montgolfière through SOI to the subsequent apoapsis, releasing it on a direct ballistic trajectory for entry at the first Titan flyby. After entry, a pilot chute would pull off the back shell, deploying the main parachute that extracts the montgolfière from its heat shield.

When the system has descended to ~40 km altitude the balloon envelope would deploy and fill with ambient air, aided by the ram effect of the continuing descent. Heat from the MMRTG suspended within the envelope would warm the air to positive buoyancy at ~8 km altitude. Once at buoyant equilibrium, the montgolfière would drift passively with the winds at 1–2 m/s, actively maintaining its nominal 10 km altitude via barometric measurements and a vent valve at the balloon's zenith.

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Fig. 2 depicts the montgolfière in stable flight. The 10 km altitude was chosen to meet all science requirements while avoiding the risk from methane icing above ~14 km and the potential risks associated with near surface operations.

The total estimated mass of the montgolfière probe and its aeroshell was estimated at 571 kg including contingency. Its 144 kg gondola includes a 25 kg payload allocation for the instruments listed in Table 3. Data would be transmitted to the orbiter at various rates during its Saturn tour via a steerable 50 cm HGA for relay to Earth.

Plans for future studies include the possibility of instrumenting the montgolfière's heat shield for geophysical measurements. Spare volume between the heat shield and the gondola might accommodate, for example, a micro-accelerometer, a radio science instrument, an acoustic package, and a magnetometer. These would be investigated as opportunity instruments to enhance the geophysical science return.

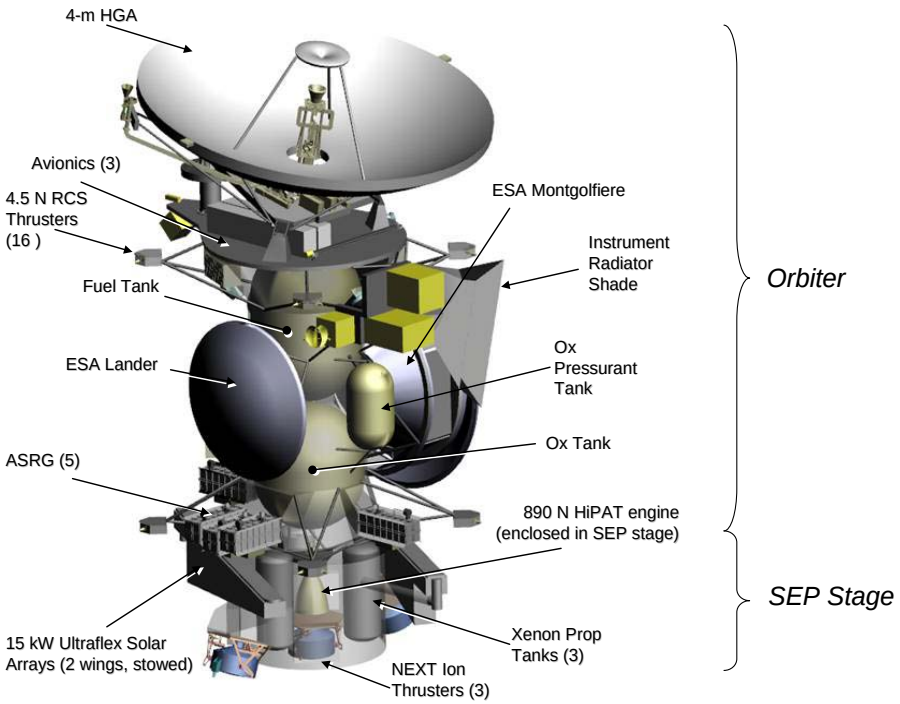


Fig. 8. Flying a chemically propelled mission to Titan would result in a flight system that has many similarities to Cassini-Huygens, however the more capable instrumentation and focused operational plan for TSSM would enable a giant leap in understanding beyond Cassini-Huygens. This Fig. shows the TSSM flight system concept.

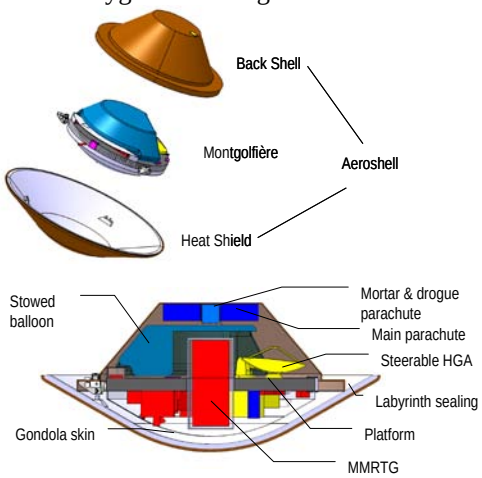


Fig. 9. Conceptual design of the montgolfière integrates Huygens heritage with balloon probe. An exploded view of entry system aeroshell is shown.

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### 3.3 Lake Lander

The orbiter spacecraft would also carry the lake lander in its aeroshell and release it during the second Titan flyby. After releasing the lander, the orbiter would be in continuous contact with it, allowing the orbiter to monitor the lander's trajectory and to collect and relay to Earth all telemetry data.

Entry and descent would largely build upon heritage from Huygens, and the early phases would be similar to those described for the montgolfière above. Unlike Huygens, in the TSSM baseline, the lander would descend on a single main parachute, thus spending more time in descent (approximately 5 hours) while performing atmospheric analysis of high northern latitudes. The floating lander design would provide enough energy to perform scientific measurements for 3–4 hours after landing in the lake.

Table 3. Model instruments for the montgolfière.

| Inst. | Description | Science Contributions |
|---|---|---|
| BIS | Balloon Imaging Spectrometer (1–5.6 µm). | Mapping for troposphere and surface composition at 2.5 m resolution |
| VISTA-B | Visual Imaging System with two wide angle stereo cameras & one narrow angle camera. | Detailed geomorphology at 1 m resolution |
| ASI/ MET | Atmospheric Structure Instrument and Meteorological Package. | Record atmosphere characteristics & determine wind velocities in the equatorial troposphere |
| TEEP-B | Titan Electric Environment Package | Measure electric field in the troposphere (0–10 kHz) and determine connection with weather. |
| TRS | > 150 MHz radar sounder | Detection of shallow reservoirs of hydrocarbons, depth of icy crust and better than 10 m resolution stratigraphic of geological features. |
| TMCA | 1-600 Da Mass spectrometer | Analysis of aerosols and determination of noble gases concentration and ethane/methane ratios in the troposphere |
| MAG | Magnetometer | Separate internal and external sources of the field and determine whether Titan has an intrinsic and/or induced magnetic field. |
| MRST | Radio Science using spacecraft telecom system | Precision tracking of the montgolfière |

Fig. 10 shows a conceptual design of the lander and an exploded view of the stowed configuration. Accommodating instrumentation and system support equipment inside the lander aids optimizing thermal balance. Environmental sensors and an omni-directional antenna would be mounted on the upper side (Fig. 10). The lander's total launch mass is estimated at 190 kg, including 32 kg of science instrumentation as listed in Table 4.

## 4. PATH FORWARD

Following completion of the TSSM study in 2008, NASA and ESA review panels evaluated the concept and identified risks that would need further attention to enable the mission to proceed. The NASA panel focused primarily on the NASA-provided orbiter and identified a number of risks to the design presented in the study that would require future action. Review by the TSSM design team recognized these risks, but determined that they are not out of the norm for missions at this stage of development and saw no "tall tent poles" requiring significant additional investment at this time.

The ESA review panel identified a number of risks, primarily related to development of the montgolfière, the one element of TSSM that is truly unique to this mission concept. A number of these technical risks were determined by the TSSM team to be excellent candidates for early mitigation activities. These included:

- Balloon deployment and inflation upon arrival at Titan
- Balloon packaging and thermal management inside the aeroshell during cruise

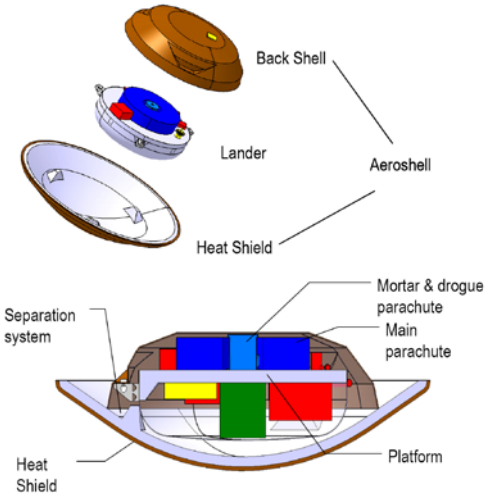


Fig. 10. Conceptual design of the lake lander in the stowed configuration. An exploded view of the Huygens heritage entry aeroshell is shown

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- Interface complexity issues between the balloon, its MMRTG, and the aeroshell
- Integration of the MMRTG during ground processing

In addition to these montgolfière-related issues, the TSSM team identified development of *in situ* instrument and sampling systems for the cryogenic environment and high performance orbiter remote sensing instruments as areas for early risk reduction activities.

To address these concerns, a multi-year plan has been developed that includes leverage of international and inter-center expertise, including participation by JPL, Caltech and CNES.

The plan being discussed would proceed in a two-step approach as shown in Figs. 11 and 12. Step 1 would

focus on risk reduction activities critical to addressing basic architectural driving questions that would allow a baseline to be defined. This would be done in parallel and in resonance with the SolarSystem2012 planetary science Decadal Survey and OPAG Titan Working Group recommendations to ensure risk reduction activities are executed in areas where they will have maximum value to a future science mission. Once preliminary risk reduction activities are completed and baseline architectures are established, the next step in the plan would proceed. In Step 2, a comprehensive and focused technical risk reduction program would advance the maturity of the technical implementation to a state of readiness required for initiation of a future mission.

Examples of key products delivered in Step 1 include:

- Balloon thermodynamic feasibility and quantification of performance margins for alternative architectures
- Selection of baseline balloon material
- Preliminary flight balloon qualification plan
- Plans for Titan analog balloon experiments (TABEX)

Table 4. Model instruments for the lake lander.

| Inst. | Description | Science Contributions |
|---|---|---|
| TLCA | Titan Lander Chemical Analyzer with 2-dimensional gas chromatographic columns and TOF mass spectrometer. Dedicated isotope mass spectrometer. | Perform isotopic measurements, determination of the amount of noble gases and analysis of complex organic molecules up to 10,000 Da. |
| TiPI | Titan Probe Imager using Saturn shine and a lamp | Provide context images and views of the lake surface. |
| ASI/ MET-TEEP | Atmospheric Structure Instrument and Meteorological Package including electric measurements | Characterize the atmosphere during the descent and at the surface of the lake and to reconstruct the trajectory of the lander during the descent. |
| SPP | Surface properties package | Characterize the physical properties of the liquid, depth of the lake and the magnetic signal at the landing site. |
| LRST | Radio Science using spacecraft telecom system | Precision tracking of lander |

- Definition of baseline aerobot architecture

Examples of key products delivered in Step 2 include:

- A detailed concept definition
- Manufacturing feasibility proven with full scale prototypes
- Packaging and storage approach validated with life testing
- Deployment and inflation approach validated with simulation and experiments
- Operational performance measured with long duration Titan analog balloon experiments

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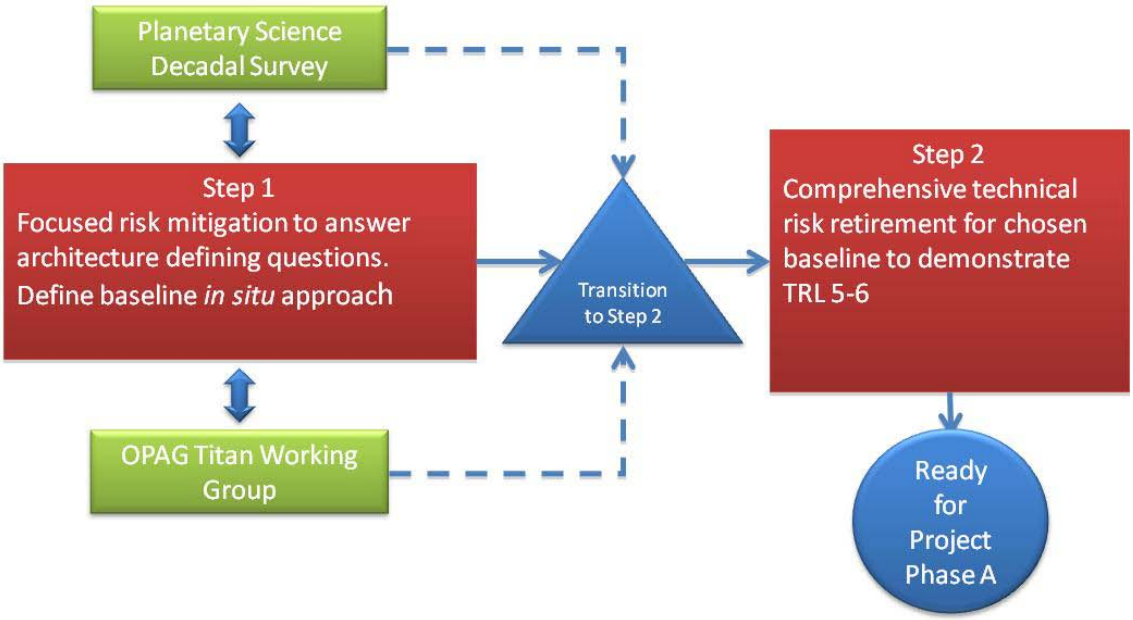


Fig. 11. Proposed plan for moving forward involves a two-step risk reduction approach.

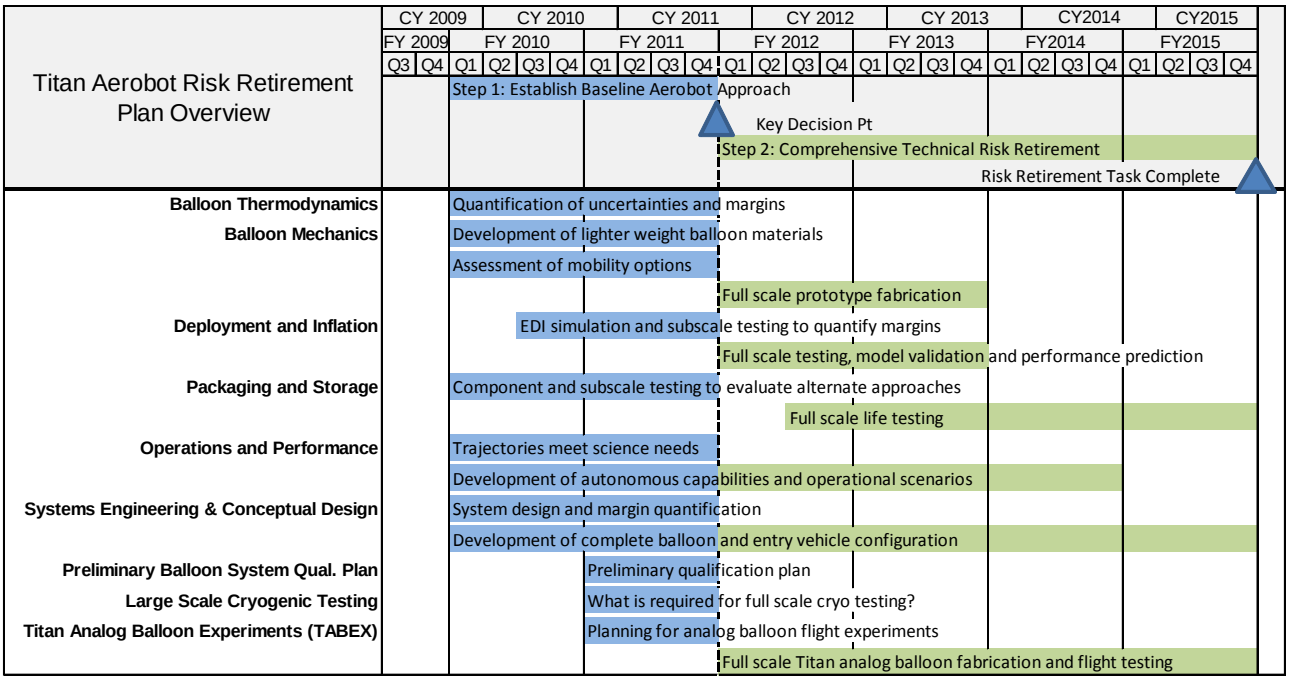


Fig. 12. Titan aerobot risk reduction plan addresses architectural defining questions leading to definition of baseline approach and followed by comprehensive risk mitigation.

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## 5. TECHNICAL FOUNDATION

The risk reduction plan would start from a solid base of analysis and testing already performed. Work has been ongoing at JPL on technologies for development and operation of planetary balloons, and much of this work has specifically focused on montgolfière designs.

### 5.1 Balloon Deployment and Inflation

The inflation of the montgolfière envelope, while similar to the parachute deployment demonstrated on the Huygens probe, is in many ways a unique operation that must be demonstrated to ensure a low-risk design. This operation has been addressed in a series of tests over the last few years. Most recently, deployment and inflation testing was performed on a 4.5 m balloon, using a configuration with a MMRTG mock-up suspended in the same manner as the proposed TSSM concept. This successful testing is illustrated in Fig. 13.

### 5.2 Balloon Cruise Thermal Management

Heat rejection from the MMRTG during cruise is a significant design challenge for the montgolfière, but one which is not unique to the TSSM concept. Currently, the Mars Science Laboratory (MSL) mission is addressing the same concern with respect to their MMRTG-based power system. The MSL solution of a remotely mounted radiator with a pumped cooling loop for the MMRTG is one which can also be adopted for the montgolfière (Fig. 14). The team will review the lessons learned from the MSL experience and incorporate those into risk reduction efforts specifically targeted to the longer duration cruise that would be a characteristic of any future Titan mission.

### 5.3 Montgolfière Performance Modeling and Testing

One of the areas most critical to development of the Titan montgolfière is that of performance modeling and testing. Given the known characteristics of the Titan atmosphere and uncertainties both in our understanding and in expected weather effects, it will be crucial to develop detailed analytical models, verified by testing. Considerable work has already begun in these areas, including computational fluid dynamics (CFD) modeling of Titan montgolfière thermodynamics (Fig. 15). Cryogenic testing of sub-scale balloons in a simulated Titan environment has been performed by Julian Nott in collaboration with JPL and Caltech to validate buoyancy and heat transfer models critical to verifying vehicle performance and assessing margins.

Fig. 13. Successful aerial deployment and inflation test on 4.5 m balloon (300–400 m altitude)

Fig. 14. ESA design for the TSSM montgolfière builds on MSL cruise configuration.

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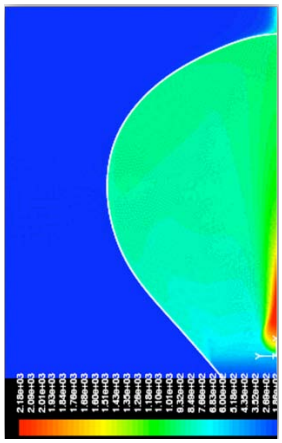

Fig. 15. CFD modeling of Titan montgolfière thermodynamics.

## 6. SUMMARY AND CONCLUSIONS

A broad range of studies assessing architecture options for the exploration of Titan have been performed over several decades by institutions including NASA, JPL, APL, ESA and CNES. While these studies have involved a variety of science definition teams with sometimes differing science objectives, a common element seen in all of these architectures is the recommendation of aerial and surface probes for *in situ* exploration. Partly as a result of these architectural findings, a significant amount of technology development has been completed toward reducing the implementation risks for such probes. This technology work has answered many initial questions, but significant additional risk reduction activities will be needed to ensure flight readiness.

To prepare for the next mission to Titan, a risk reduction plan has been developed that responds directly to the major findings identified by NASA and ESA review boards in their review of the 2008 TSSM concept. This plan includes joint JPL and CNES efforts to mature the readiness of a Titan montgolfière probe, as well as efforts to demonstrate readiness of cryogenic *in situ* instruments and sampling systems. Completion of these activities is key to enabling future multi-probe *in situ* missions to Titan.

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